Observations of Internal Waves on an Oceanic Boundary Slope Without a Shelf Region (Hawaiian Islands)

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LONG-TERM GOAL

Our long-term goal is to describe and understand spatial variations of the internal wave field near topography.

OBJECTIVES

Our principal suppositions are that variations in the energy, frequency content and wavenumber content of the internal wave field near topography will be related to spatial differences of environmental parameters such as distance to the boundary, slope magnitude and/or curvature, buoyancy frequency, and so on, as well as to the propensity of the boundary configuration to support trapped oscillations that propagate freely only along the boundary (such as edge and Kelvin waves). Our objective is to test these suppositions with in situ measurements of the current and temperature fields.

The suppositions just described, and the investigative approach described below, arose from published descriptions of the internal wave field in the presence of topography, which paint a rather confused picture of how the internal wave field is modified by reflections from a sloping boundary. Eriksen (1982) brought to the attention of physical oceanographers the idea that reflection of internal waves from a sloping bottom results in a re-distribution of energy in wavenumber space producing enhancement of kinetic energy (above that expected for open ocean internal waves) at the critical frequency near-bottom (where the critical frequency, $\omega_c^2 = N^2 \sin^2\alpha + f^2 \cos^2\alpha$, where N is the buoyancy frequency, f is the local Coriolis frequency, and α is the bottom slope). [From linear theory, reflection of an internal wave at the critical frequency for a particular slope results in the reflected wave having zero wavelength and infinite energy density.] While this idea was not new, the examination of current and temperature spectra for this phenomenon had not been approached in any systematic way before Eriksen's (1982) outstanding demonstration of the phenomenon.

Curiously, the energy enhancement at the critical frequency did not exist at the continental slope sites presented by Eriksen (1982), though it did exist at Muir Seamount and a near-equatorial, mid-ocean ridge site. One difference between Eriksen's (1982) continental slope site and the others he presented was that the continental slope site had the weakest slope. Combined with Eriksen's (1995, 1998) finding of orders of magnitude enhancement of kinetic energy at the relatively high critical frequency (0.42 cph) over the flank of Fieberling Guyot, the suggestion is clear that the larger slopes result in greater energy enhancement at the critical frequency. But is this the whole story?

Gilbert (1993) conducted an examination of current meter records from 13 sites on the slope and rise off Nova Scotia. He found enhancement of kinetic energy or cross-isobath alignment of motion (another prediction of the linear theory) at the critical frequency only about half of the time. He argued that the lack of critical frequency enhancement was due either to the concavity of the local topography at many sites (such as at the base of the slope) or to the fact that when the slope was weak, such that the critical frequency was close to f , the ambient wave field is composed of waves near their turning latitudes so that their propagation is to the east or west, implying azimuthal incidence angles of around 90 degrees for most of the Scotian slope and rise sites (that is, the waves would hit the slope at a small grazing angle rather than at a more onshore-offshore angle, since the isobaths run primarily east-west). At these grazing angles of azimuthal incidence there is little change in onshore/offshore wavenumber upon reflection so that one would not see much enhancement of energy at the critical frequency. Gilbert (1993) also remarks on non-linear processes that could alter the expected (from linear theory) characteristics of reflected internal waves.

Gilbert's (1993) speculations are provocative. Many additional sites must be sampled however to sort out the competing processes. The available Hawaiian dataset (described below) is rich in topographic settings (i.e., slope magnitude and azimuth, and topographic curvature). Note also that an admitted uncertainty in Gilbert's (1993) work was his lack of accurate topography. This won't be a problem here as a digital bathymetric database has been constructed for the Hawaiian Is. under the support of ONR (e.g., see Keating, 1995).

APPROACH

For this initial exploratory investigation, in order to minimize the number of complicating factors, we have chosen to study the internal wave field near topographic features that are not proximal to continental shelves or strong mean currents, both of which could alter the characteristics of the internal wave field over a nearby sloping bottom. The Hawaiian Islands are a logical location for this investigation for two principal reasons. First, the islands are located in the middle of a Garrett and Munk (hereafter, GM) internal wave pool; that is, except perhaps very close to the surface and bottom boundaries, the ambient internal wave field surrounding the islands is expected to be well described by a canonical spectral model first popularized by Garret and Munk (1972, 1975) then refined by Cairns and Williams (1976), Muller et al. (1978) and others. This situation can be contrasted, for instance, to the east coast of the United States where the presence of the Gulf Stream may result in non-GM characteristics for the internal wave field just off the continental slope, so that delineation of changes to the internal wave field attributable to the slope may be more difficult to pinpoint independently from the wave-mean flow interaction effects.

Second, there have been numerous investigations of the current and temperature fields around the Hawaiian Islands for engineering purposes (sewage dispersion studies, telephone cable path surveys, etc.) which have resulted in large amounts of data recorded very near the island flanks (usually within 10-100m of the bottom), in many distinctly different topographic settings (e.g., concave vs. convex bottom curvatures). Much of this data has been acquired from local ocean technology companies over the past 5 years by the faculty of the University of Hawaii. These data have not been examined previously for extraction of the information they contain about the internal wave field. Our approach to achieving the objectives above is to produce statistical and spectral descriptions of the internal wave field from the Hawaiian data just described, documenting deviations from the GM paradigm, and then categorizing these deviations in terms of bottom slopes and curvatures (determined from highly accurate swath bathymetry surveys around the Hawaiian Islands), stratification variations (using the numerous stratification profile data that usually accompanied the engineering surveys noted above), critical frequency variations, etc.

WORK COMPLETED

We have examined time series and calculated energy spectra of 235 separate records of horizontal currents and 122 separate records of temperature to evaluate data quality and appropriateness for this investigation. 66 records of horizontal currents and 25 records of temperature were discarded due to apparent instrumental errors, gaps, precision problems and so forth. The remaining data, some of which needed to be edited for bad points or gaps, comprise a total of over 81 years of currents from 27 distinct sites ranging in depth from 100m to 2000m. Most of the sites have data taken within 10 meters of the bottom, and nearly all have data taken within 100 m of the bottom, making this combined dataset quite valuable for examining internal wave behavior in the presence of a variety of bottom configurations.

We have begun the process of quantitatively defining the environmental characteristics upon which we anticipate the internal wave reflection process will depend, e.g., bottom slope and curvature at each site are being estimated from digital swath bathymetry datasets, mean buoyancy frequency and its variability are being estimated from vertical profiles of temperature and salinity, and the mean critical frequency and its variability are being estimated from these slopes and buoyancy frequencies per the equation above.

We have also begun calculating higher-level analysis products (e.g., rotary spectra, polarization, ellipse stability and orientation) to provide as complete characterizations as possible of the internal wave field. Some horizontal coherence functions have been calculated to look at alongslope propagation characteristics, and more are planed.

RESULTS

To date we have found that the range of near-bottom enhancement, relative to the canonical GM spectrum, of the internal wave energy at the critical frequency spans a large range from being almost nothing to being equal to that found at Fieberling Guyot (Eriksen, 1998) which has the largest enhancement that has ever been observed. Figure 1 displays several examples of energy density spectra

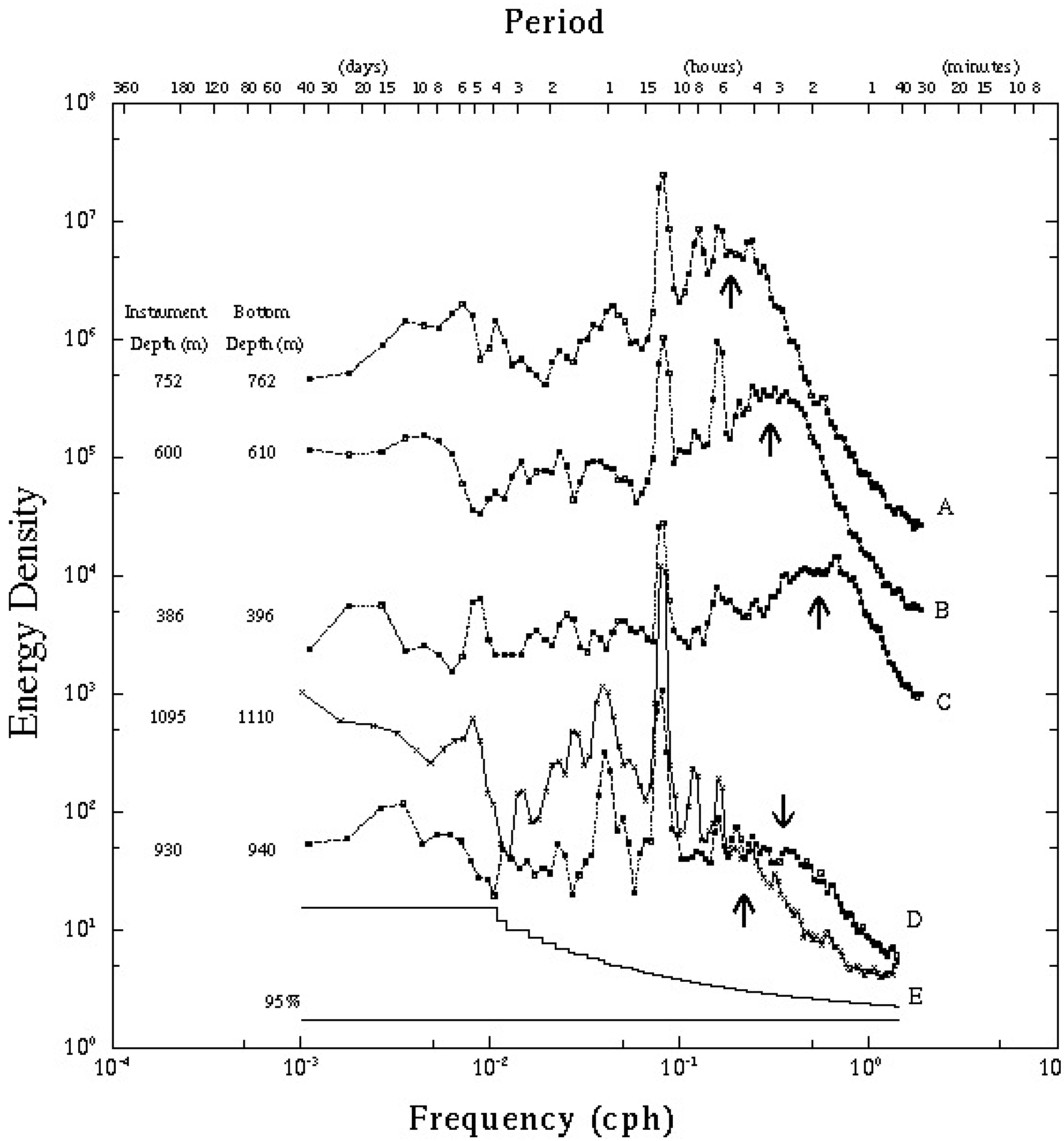

Figure 1. Energy density spectra of (approximately) cross-isobath currents from five locations. The instrument and bottom depths are displayed on the left. Note that all instruments are within 15 meters of the bottom. The arrows indicate the approximate critical frequency defined in the text. Sites A, B & C are approximately in-line off the southwest coast of Oahu; the separation distances are ~1.25 km between A & B and B & C. The increasing critical frequency from A to B to C is due both to increasing slope and increasing buoyancy frequency at the shallower depths. Sites D & E between the islands of Maui and Hawaii are separated by ~0.8 km. The different critical frequencies at sites D & E are principally due to different slopes. Every other point plotted is independent. The 95% confidence intervals for independent points are indicated at the bottom.

of the component of the horizontal current that is oriented approximately cross-isobath (this is the component expected to show the greatest enhancement of energy at the critical frequency). Note the large range of enhancement, from almost none at site E to very strong at site A. So far, we have not detected any conclusive relationship between these energy enhancements and environmental variables, 'though this part of the investigation is only just beginning. We can state however, that the curvature of the bottom does not appear to have the simple correspondence to energy enhancement as postulated by Gilbert (1993), who surmised that a bottom profile with convex curvature cross-slope would lead to greater energy enhancement at the critical frequency than concave bottom profiles. We find significant enhancement over convex and concave bottoms alike (e.g., in Fig. 1, C, with clear energy enhancement at the critical frequency, is from a site with concave curvature of the bottom in the cross-isobath direction, while D & E, with weak or no energy enhancement, are from convex sites). Other factors must be important.

What we believe to be an important result is the observation that the amount of enhancement of energy at the critical frequency near bottom appears to be a sensitive function of distance. Sites within 800 m of each other (e.g., D & E in Fig. 1), that yet have different slopes, exhibit different magnitudes of energy enhancement at the critical frequency.

From the few higher level analyses completed so far, we have found no deviation from the linear prediction that the current ellipses should be oriented across isobaths at the critical frequency. The stability of the orientation of the current ellipse as frequency varies across the critical frequency bands suggests that Rhines' (1970) trapped modes are not present. Surprisingly, however, where data is available from compact arrays we find high horizontal coherence right at the critical frequency with zero phase lag (e.g., between locations A, B & C). The meaning of this last result is unclear.

IMPACT/APPLICATION

The observation, logical in retrospect, that the internal wave energy levels around the critical frequency vary substantially over short distances, in apparent accord with slope changes, suggests that accurate models (and, subsequently, prediction) of internal wave energy near topography (as might be needed for acoustic propagation models) will require very accurate bathymetric data.

TRANSITION

None to report at this time.

RELATED PROJECTS

The results presented here were used in the design of an experiment that has been proposed to the National Science Foundation to study the impact of flow-topography interactions on producing sub-thermocline mixing. Both Luther and Merrifield are co-PIs on this proposal that includes over 20 co-PIs and is led by R. Pinkel (SIO). The principal focus of this proposal is on the role of internal tides in producing the enhanced mixing, but the existence of alternative sources of energy for mixing (such as from the high shear generated by higher than normal levels of energy around the critical frequency) have to be acknowledged and considered. Parts of the proposed NSF fieldwork will collect data that will be useful for looking at the characteristics of the internal wave field near the boundary.

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